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Abstract

Binding information in short-term memory and in long-term memory are functions sensitive to Alzheimer's disease. They have been found to be affected in patients who meet criteria for familial Alzheimer's disease due to the mutation E280A of the PSEN1 gene. However, only short-term memory binding has been found to be affected in asymptomatic carriers of this mutation. The neural correlates of this dissociation are poorly understood. The present study used diffusion tensor MRI to investigate whether the integrity of white matter structures could offer an account. A sample of 19 familial Alzheimer's disease patients, 18 asymptomatic carriers and 21 non-carrier controls underwent diffusion tensor MRI, neuropsychological and memory binding assessment. The short-term memory binding task required participants to detect changes across two consecutive screens displaying arrays of shapes, colours, or shape-colour bindings. The long-term memory binding task was a Paired Associates Learning Test. Performance on these tasks were entered into regression models. Relative to controls, familial Alzheimer's disease patients performed poorly on both memory binding tasks. Asymptomatic carriers differed from controls only in the short-term memory binding task. White matter integrity explained poor memory binding performance only in familial Alzheimer's disease patients. White matter water diffusion metrics from the frontal lobe accounted for poor performance on both memory binding tasks. Dissociations were found in the genu of corpus callosum which accounted for short-term memory binding impairments and in the hippocampal part of cingulum bundle which accounted for long-term memory binding deficits. The results indicate that white matter structures in the frontal and temporal lobes are vulnerable to the early stages of familial Alzheimer's disease and their damage is associated with impairments in two memory binding functions known to be markers for Alzheimer's disease.

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Authors' contributions:

MAP contributed to the study design, data collection and analysis and the preparation of the manuscript; **HS** contributed to the data analysis and the preparation of the manuscript; **SA** contributed to the study design, data analysis, and the preparation of the manuscript; **MB** contributed to the data analysis and the preparation of the manuscript; **AL** and **FL** identified participants for this study, performed the clinical and neuroimaging assessment and commented on the manuscript; **SDS** contributed to the study design and preparation of the manuscript.

Keywords: Alzheimer's disease; Memory; Structural MR Imaging; Biomarkers; Psychometry

Abbreviations: Default mode network (DMN); Diffusion tensor MRI (DT-MRI); Familial Alzheimer's disease (FAD); Fractional anisotropy (FA); Functional MRI (fMRI); Long-term memory (LTM); Mean diffusivity ($\langle D \rangle$); Mild cognitive impairment (MCI); Mini-Mental State Examination (MMSE); Paired Associates Learning (PAL); Region of Interest (ROI)

[Centrum semiovale (CS); Genu corpus callosum (gCC); Hippocampal part of the cingulum bundle (CGH); Inferolateral region of the frontal white matter (iFWM); Middle frontal white matter (mFWM); Splenium corpus callosum (sCC)]; Short-term memory (STM); Visual STM (VSTM); Wisconsin Card Sorting test (WCST)

Introduction

Although Alzheimer's disease appears to grossly impair integrative memory functions both in short-term memory (STM) (Della Sala *et al.* 2012; Parra *et al.*, 2009; 2011) and in long-term memory (LTM) (Buschke *et al.*, 1999; O'Connell *et al.*, 2004; Swainson *et al.*, 2001), these impairments seem to have different origins. STM binding supports the temporary retention of *conjunctions* of features within object representations, a function needed for the formation of new identity. Associative learning (i.e., LTM binding) enables a flexible representation of the *relations* between the stimulus' parts, each holding its own identity and retaining its individual access (Mayes *et al.*, 2007; Moses and Ryan, 2006).

STM binding deficits have been observed in asymptomatic carriers of the mutation E280A of the PSEN1 gene (E280A-PSEN1) who still perform normally on LTM binding tasks, such as the Paired Associates Learning (PAL) test of Wechsler Memory Scale (Wechsler, 1997) which has been found to be sensitive to prodromal and clinical Alzheimer's disease (Duchek *et al.*, 1991; Elias *et al.*, 2000). In fact, STM and LTM binding deficits in these individuals do not correlate (Parra *et al.*, 2011) reinforcing the notion of different neural substrates. Whereas LTM binding relies on the integrity of cerebral grey matter structures such as the hippocampus, which is known to be targeted by Alzheimer's disease in its sporadic (Echavarri *et al.*, 2010) and familial variants (Quiroz *et al.*, 2010), a recent functional MRI (fMRI) study indicates that the STM binding function investigated below does not (Parra *et al.*, 2014). Recent behavioural studies have further expanded the evidence in favour of dissociations between these two types of memory representation (Parra *et al.*, 2013).

The STM binding task asks participants to hold together in memory features processed in separate brain regions whereas the LTM binding task (i.e., PAL) asks participants to learn the association between two words. These tasks require effective brain connectivity (Genon *et*

al., 2013; Koenig *et al.,* 2005; O'Reilly *et al.*, 2003). It is well recognized that Alzheimer's disease leads to a disconnection syndrome (Bozzali *et al.*, 2011; Gili *et al.*, 2011), and it is therefore hypothesized that such a syndrome underlies this specific cognitive deficit.

An Alzheimer's disease disconnection syndrome has been well characterised using EEG-based methods (Cook and Leuchter, 1996; Dunkin *et al.*, 1994) and more recently by resting state fMRI (Buckner *et al.*, 2005; Buckner *et al.*, 2008). Abnormal patterns of brain connectivity in the default mode network appear to characterise the transition from normal ageing to mild cognitive impairment (MCI) and from MCI to Alzheimer's disease (Miao *et al.*, 2011; Pihlajamaki and Sperling, 2009). Furthermore connectivity deficits as assessed by electrophysiological and neuroimaging techniques significantly correlate with cognitive decline both in prodromal (Chua *et al.*, 2008) and clinical Alzheimer's disease (Duan *et al.*, 2006; Medina and Gaviria, 2008). However, the precise contribution of grey and white matter disruptions to the disconnection syndrome, and its cognitive implications, remains unclear (Johnson *et al.*, 2010; Oishi *et al.*, 2011).

Abnormalities in white matter integrity can now be more precisely investigated *in vivo* using diffusion tensor MRI (DT-MRI; Basser, 1995), and have been used to investigate the underpinnings of cognitive deterioration in individuals at increased risk for Alzheimer's disease such as those with MCI (Bozzali *et al.*, 2011; Chua *et al.*, 2008; Stebbins and Murphy, 2009). These studies are characterised by a great variability in the localization of abnormalities within white matter tracts in MCI patients, e.g. in medial temporal lobe (Fellgiebel *et al.*, 2004; Kantarci *et al.*, 2005), projection fibres including posterior cingulum, thalamic radiations and fornix (Kiuchi *et al.*, 2009; Zhuang *et al.*, 2010), association fibres including superior and inferior longitudinal fasciculi and inferior fronto-occipital fasciculus (Medina *et al.*, 2006; Zhuang *et al.*, 2010), and white matter underlying frontal, temporal, parietal and occipital lobes (Douaud *et al.*, 2011; Medina *et al.*, 2006; Zhuang *et al.*, 2010).

Nevertheless, recent evidence suggests that these abnormalities are related to cognitive decline in MCI patients and seem to develop very early along with still subtle grey matter damage (Bozzali *et al.*, 2011; Gili *et al.*, 2011; Sexton *et al.*, 2011).

Studies of preclinical cases of familial Alzheimer's disease have also revealed decreased white matter integrity in columns of the fornix and left orbitofrontal lobe in mutations carriers who have gone on to develop familial Alzheimer's disease , i.e. PSEN1, mutations A431E, L235V, G206A and V717I (Ringman *et al.*, 2007). These patients were completely asymptomatic (Clinical Dementia Rating = 0, cognitively unimpaired) at the time of assessment indicating that reduced white matter integrity may precede the development of clinical symptoms (Ukmar *et al.*, 2008; Wang *et al.*, 2012). Similar disruptions are also observed in other non-Alzheimer's disease dementias (Borroni *et al.*, 2007; Sweed *et al.*, 2012), suggesting that DT-MRI alone may lack specificity in early identification of Alzheimer's disease. However, identifying early DT-MRI abnormalities associated with memory binding impairments, which are known to be sensitive to Alzheimer's disease, would help overcome this limitation. If this hypothesis proves valid, combining assessment of DT-MRI and memory binding performance may unveil brain abnormalities which are more closely related to Alzheimer's disease pathology. The present study therefore firstly investigated whether differences in white matter integrity detected with DT-MRI are related to STM binding deficits in carriers of the mutation E280A- PSEN1 who were either asymptomatic or had recently met criteria for Alzheimer's disease. Secondly the study compared regional DT-MRI metrics with performance on both STM binding and LTM binding tasks to investigate further the neural dissociation between these two processes.

Methods

Participants

The participants were members of a large kindred from the Colombian province of Antioquia, South America. They carry the gene mutation E280A of presenilin-1 which invariably leads to an autosomal dominant early-onset familial Alzheimer's disease. This variant of familial Alzheimer's disease becomes clinically detectable at 47 years of age, on average; see (Lopera *et al.*, 1997) for a clinical description. Mutation carriers either in the symptomatic or pre-symptomatic stages of the disease, along with members their family, regularly attend clinical and research appointments at the Health Unit of the Neuroscience Centre of the University of Antioquia. This Health Unit has been monitoring this population for more than 20 years. The participants were approached by the responsible consultants who introduced the study and invited them to take part. All the patients who attended the Unit during the time of the study were given the opportunity to participate. Moreover, patients and relatives who had previously expressed an interest in research and whose contact details were held in the centre's database were also contacted. Only those expressing an interest were taken forward to the enrolment process which began with the informed consent. The genetic status of these patients is unknown to the centre's staff and was not revealed to members of the research team until the recruitment process had been completed. This was done using anonymous codes. The study protocol was approved by the Ethics Committee at University of Antioquia, Colombia.

The assessment protocol for all the participants consisted of three phases. First, participants who were not in the centre database (new to the Centre) underwent genetic screening to confirm or exclude the presence of the mutation using the methodology reported by the Alzheimer's disease Collaborative Group (Clark *et al.*, 1995). Second, all the participants underwent neurological and neuropsychological assessments carried out by expert clinicians

and neuropsychologists. Third, all the participants underwent DT-MRI assessment. The first two phases allowed us to allocate participants to three groups: 1) participants with familial Alzheimer's disease caused by the E280A single presenilin-1 mutation, 2) carriers of the mutation who did not meet Alzheimer's disease criteria and who were asymptomatic at the time of testing, and 3) healthy individuals who did not carry the gene mutation, were healthy as confirmed by the clinical interview and were relatives of the members of the other two groups (healthy controls).

A sample of 58 participants entered the study. Data from 32 participants (HC = 6, AC = 16, FAD = 10) were drawn from previous studies investigating visual STM (VSTM) binding (Parra *et al.*, 2010; 2011). The other new participants were assessed with the same protocol. The first group comprised 19 familial Alzheimer's disease patients diagnosed according to the criteria established by the Diagnostic and Statistical Manual of Mental Disorders (4th edition, text revision), and the National Institute of Neurological and Communicative Disorders and Stroke and the Alzheimer's Disease and Related Disorders Association (NINCDS-ADRDA) group (McKhann *et al.*, 1984). Second, the asymptomatic carriers group consisted of 18 participants who met neither Alzheimer's disease nor MCI criteria at the time of the testing but who were positive for the E280A mutation. Third, the healthy controls group included 21 non-carriers who were relatives of the familial Alzheimer's disease patients and asymptomatic carriers. Additional inclusion criteria for the control participants included 1) negative history of neurological or psychiatric disorders, 2) a Mini-Mental State Examination (MMSE) score equal or greater than 24, and 3) no memory complaints as documented by a self-report and family questionnaire.

Asymptomatic carriers and healthy controls were matched according to age, the number of years spent in formal education, and the MMSE scores (see Table 1). On average, familial Alzheimer's disease patients were older and less educated than the two other groups.

Insert Table 1 about here

Each participant underwent a colour vision assessment using Dvorine pseudo-isochromatic plates (Dvorine, 1963) and a binding perception condition. These assessments were undertaken to rule out the possibility that poor performance on the STM binding task could result from visual or perceptual difficulties. None of the participants recruited for the present study were excluded due to colour vision or perceptual binding problems.

Behavioural Assessment

Neuropsychological battery

The neuropsychological battery comprised Spanish translations of the MMSE (Ardila et al., 2000), the PAL task (Wechsler, 1997), Verbal (Letter-FAS, adapted from Sumerall *et al.*, 1997) and Animal Fluency tests (from Morris *et al.*, 1989), the Copy and Recall of the Complex Figure of Rey-Osterrieth (Osterrieth, 1944), Part-A of the Trail Making test (Reitan, 1958), the Boston Naming test (Kaplan *et al.*, 1983), the Wisconsin Card Sorting test (WCST; Berg, 1948), and the Word List test (from Morris *et al.*, 1989).

Visual short-term memory task

The VSTM task assessed memory for shapes (see Figure 1a), colours, or combinations of the two. Stimuli were randomly selected from a set of eight shapes and eight colours and presented as individual features or as features combined into integrated objects. Each type of stimulus was presented in a separate condition. Three experimental conditions were used (see

Figure 1b), each consisting of 15 practice trials followed by 32 test trials leading to a total of 96 test trials per task. Trials were fully randomized across participants and conditions were delivered in a counter-balanced order. In the `**Shape only'** and `**Colour only'** conditions, arrays of shapes or colours were presented in the study display. In the test display for the `different' trials, two new shapes or colours from the study array were replaced with two new shapes or colours. Hence, in these conditions, only VSTM for individual features was required to detect a change. In the `**Shape-colour binding'** condition, combinations of shapes and colours were presented in the study display. In the test display for ``'different' trials, two shapes swapped the colours in which they had been shown in the study display. Hence, memory for bindings of shape and colour in the study display was required in order to detect this change. No shape or colour was repeated within a given array. 50% of the test trials were `same' trials (the study and test displays presented identical items) and 50% were 'different' trials.

Insert Figure 1 A and B about here

Trials began with a fixation screen presented for 500 ms. This was followed by an array presented for 2000 ms on a 15" PC screen using a 3 x 3 virtual grid ('study display'). After a 900 ms retention interval, participants were presented with 'test display' and were required to respond orally whether the test stimulus was the 'same' or 'different' to the one presented in the 'study display'. The experimenter entered participants' responses using the keyboard.

Memory load was manipulated to match the general group performance by presenting asymptomatic carriers and healthy controls with arrays of three items and familial

Alzheimer's disease patients with arrays of two items. Previous studies have shown that manipulating the memory loads allows performance levels in the baseline memory condition to be equated across groups and, thus, any differences between groups in VSTM binding performance cannot be attributed to the baseline differences in memory for single features (Parra *et al.*, 2010).

DT-MRI Assessment

Data collection and pre-processing

DT-MRI data were collected using a Siemens Symphony Vision 1.5 T (Siemens Healthcare Sector, Erlangen, Germany) clinical scanner, and consisted of one T2-weighted and sets of diffusion-weighted (b = 1000 s/mm2) single-shot, spin-echo, echo-planar (EP) volumes acquired with diffusion gradients applied in 12 non-collinear directions. Fifty contiguous slice locations were imaged with a field-of-view of 220 × 220 mm, an acquisition matrix of 128 × 128 and a slice thickness of 3 mm, giving an acquisition voxel dimension of 1.72 × 1.72 × 3 mm. The repetition and echo times for each EP volume were 7.2 s and 90 ms.

The DICOM format (http://medical.nema.org) magnitude images were converted into NIfTI-1 format (http://nifti.nimh.nih.gov). Using tools freely available in FSL (FMRIB, Oxford, UK; http://www.fmrib.ox.ac.uk), the DT-MRI data were pre-processed to extract the brain, and bulk patient motion and eddy current induced artefacts removed by registering the diffusion-weighted to the T2-weighted EP volume for each subject (Jenkinson and Smith, 2001). From these MRI data, mean diffusivity ($\langle D \rangle$) and fractional anisotropy (FA) volumes were generated for every subject using DTIFIT.

ROI placement

Semi-automated region-of-interest (ROI) analysis was performed using 'in house' software

written in MATLAB (The MathWorks, Natick, MA, USA) that allowed multiple small square ROIs to be placed on the T2-weighted EP volumes and then overlaid on the co-registered ⟨D⟩ and FA maps automatically using locations defined in Montreal Neurological Institute (MNI; http://www.bic.mni.mcgill.ca) standard space. The software allows the user to interactively move ROIs if standard to native space registration errors cause white matter ROIs to be placed over cerebrospinal fluid (CSF) or grey matter structures.

The procedure for obtaining the FA and ⟨D⟩ values for each ROI is presented in Figure 2A. First, MNI coordinates were defined in standard space for each ROI using the ICBM-DTI-81 white matter atlas (Oishi *et al.*, 2011) and then selected in FSLview 3.1.8. Either 4, 6 or 12 square ROIs were defined for each brain structure depending on its size in horizontal view, sizes of which were 3 x 3 x 1 voxels (see Supplementary Table 1 for MNI coordinates of each ROI and Supplementary Table 2 for parameters used to place ROIs). Differences in size of the chosen ROI are explained by anatomical factors (e.g., tract dimension as for the corticospinal tract) and underlying theory (e.g., middle frontal white matter which encompasses tracts found to be impaired in Alzheimer's disease). An aim of this study was to unveil biomarkers of cognitive impairment in preclinical Alzheimer's disease. We therefore maximized the likelihood of identifying DTI correlates of behavioural impairments.

Several square ROIs were used for each structure in order to reduce the effects of differences in individual placement. Next, the coordinates were mapped from standard space to each individual's T2-weighted EP volume using the inverse of the transformation matrix from native to standard space (MNI152_T1_1mm_brain template) determined using affine registration (12 degrees of freedom) provided by FSL's FLIRT. The placement of the ROIs in native space was then checked to ensure no overlap with either CSF or grey matter. The T2-weighted EP volumes were used to define the ROIs to avoid biasing their placement by the underlying FA and ⟨D⟩ values; see (Bozzali and Cherubini, 2007). Minor adjustments to ROI

position were performed by an investigator blind to subjects' genetic or clinical status. It was only to some ROIs whenever they fell into CSF or grey matter. Finally, the values for FA and ⟨D⟩ were obtained for each square and then averaged for each ROI separately.

We chose ROIs which met two criteria. First, they comprise tracts relevant to the specific memory functions investigated in this study and second, they have been found to be affected in the preclinical and in the clinical stages of Alzheimer's disease. The ROIs targeted by the Alzheimer's disease pathology (e.g., amyloid plaques) in the preclinical stages were of particular interest (Buckner *et al.*, 2005; Fleisher *et al.*, 2012). The selected ROIs that met these criteria are shown in Figure 2B (see also Supplementary Table 1 for the MNI coordinates). They included two regions of the corpus callosum, the genu (central body) corresponding to forceps minor (gCC, Fig 2B-(a)) and the splenium which includes the forceps major (sCC, Fig 2B-(b)), both interhemispheric tracts. Two regions were selected from the frontal lobes. One labelled middle frontal white matter (mFWM, Fig 2B-(c)) which encompasses the inferior frontal-occipital fasciculus, the anterior thalamic radiations and the lateral projections of the genu which run ipsilaterally. The other was a more inferolateral region of the frontal white matter through which runs the superior longitudinal fasciculus (iFWM, Fig 2B-(d)). In the medial temporal lobe we selected the hippocampal part of the cingulum bundle (CGH, Fig 2B-(e)). White matter tracts, including cingulum, bilateral superior frontal-occipital fasciculus, and the genu of the corpus callosum are known to connect regions of the default mode network (DMN) (Teipel *et al.*, 2010) which have been consistently found to be affected by Alzheimer's disease (Agosta *et al.*, 2011; Sorg *et al.*, 2009; Wu *et al.*, 2011). Furthermore, regions of the DMN, such as the frontal lobes, are associated with working memory performance (Koshino, Minamoto, Yaoi, Osaka, & Osaka, 2014) whereas medial temporal lobe regions are involved in long-term associative memory functions (Ward *et al.*, 2014). These regions have shown a synergistic relationship following

brain damage (Maccotta *et al.*, 2007). The final ROI we considered was the centrum semiovale (CS, Fig 2B-(e)) which covers large areas of the corticospinal tract. This was chosen on the assumption of preserved motor functions in the early stages of Alzheimer's disease (Huang *et al.*, 2012; Rose *et al.*, 2000) and as such served as a comparative control region. One other region found to be relevant in previous DT-MRI studies involving preclinical Alzheimer's disease is the fornix (Molinuevo *et al.*, 2014; Racine *et al.*, 2014; Ringman *et al.*, 2007). This is a projection tract which connects the medial temporal lobe to other limbic structures and is known to be involved in memory functions (Boespflug *et al.*, 2014). However, technical limitations (i.e., small size and imprecise boundaries) prevented the inclusion of this ROI in our analysis. Nevertheless, we included the CGH, a white matter tract linking the hippocampus and para-hippocampal cortex to the posterior cingulate cortex, known to be relevant for memory function and sensitive to Alzheimer's disease pathology (Catheline *et al.*, 2010; Villain *et al.*, 2008).

Finally, ROI selection was independently performed by two investigators of this study. The aim of this procedure was to assess inter-rater reliability of region of interest placement. To this aim, rater 2 (MB) randomly selected a subset of participants (n=5) from the dataset initially processed by rater 1 (HS). We report on the index of reproducibility and coefficient of variation for the two DT-MRI metrics.

Insert Figure 2 A and B about here

Statistical analyses

Statistical analyses were performed in R version 3.1.1 (R Development Core Team). Group

differences in background variables (e.g., age, education, and MMSE score) were examined with ANOVA using Tukey's test for post-hoc comparisons. Hemispheric differences in FA and ⟨D⟩ values were examined with *t*-tests.

Group differences in behavioural tasks were tested with linear regression. A model with age, education, and group was created for each task (task ~ age + education + group) to test for the relationship between these variables and task performance. Post-hoc group comparisons were performed with using pairwise least-squares means comparison with the Tukey's correction for multiple comparisons using lsmeans function from the lsmeans package. Least-squares means were used in order to extract the group means after controlling for age and education effects.

Group differences in DT-MRI metrics (i.e., FA and ⟨D⟩ values) for each ROI were examined with linear regression. A simple model with group as a predictor was created for each ROI **(DT-MRI ~ group)** and post-hoc group comparisons were performed with pairwise Tukey's test. This model, and the subsequent models in which group was entered as a predictor, allow the assessment of associations between dependent variables (i.e., DT-MRI measures and behavioural) and group membership. The rationale behind these regression models is that they fit the first intercept and slope for the association between such variables in the first group (in our analysis this was the healthy control group). Then, the models test whether group membership (i.e., asymptomatic carriers or familial Alzheimer's disease patients) modifies such associations. The relationship between task performance and DT-MRI metrics was investigated with linear regression by fitting models with DT-MRI variables as predictors for task performance **(task ~ DT-MRI)**.

Finally, the relationship between task performance, DT-MRI variables, and group membership was examined with correlation and linear regression. Firstly, we examined the correlation between task performance and DT-MRI variables in each ROI separately in all

groups. Second, to visualize the results, we examined the significant correlations revealed in step one more closely with linear regression. The relationship between task performance, group identity and DT-MRI parameters was investigated with linear regression by predicting task performance with group identity, DT-MRI parameter, and their interaction (**task ~ group * DT-MRI**). To account for multiple statistical comparisons, all p-values shown were False Detection Rate (FDR) corrected.

A recent study confirmed that the method reported here to place ROIs and derive DT-MRI variables provides good reliability (Pettit *et al.*, 2013). However, we performed further inter-rater reliability analysis for the ROIs chosen for the present study. To this aim, placement of the ROIs was independently performed by two investigators of this study. Rater 2 (LP) randomly selected a subset of participants (n=5) from the dataset initially processed by rater 1 (HS). We report on the index of reproducibility and coefficient of variation for the two DT-MRI variables.

Results

Behavioural results

Results from group comparisons of behavioural variables are presented in Table 2. Familial Alzheimer's disease patients performed significantly worse than healthy controls on all neuropsychological and VSTM binding tasks except for the WCST and Letter fluency task. Familial Alzheimer's disease patients performed significantly worse than the asymptomatic carriers on all tasks except for the WCST and colour-colour binding task. Asymptomatic carriers performed significantly worse than healthy controls on the shape-colour binding condition of the VSTM task only.

Education was associated with task performance on the Trail Making Test, Animal Fluency, and Boston Naming Test. Age was not significantly associated with performance in any of the

tasks. Importantly, age and education were not associated with VSTM shape-colour binding or PAL tasks, so further analyses with these tasks of interest did not include age or education as a covariate.

Insert Table 2 about here

DT-MRI metrics

The inter-rater reliability analysis indicated excellent reproducibility of ROI measurements with the standard deviation of the difference between repeated measures of ⟨D⟩ and FA being 37 x 10^{-6} mm^2/s (mean of measurements 739 x 10^{-6} mm^2/s) and 0.034 (mean 0.349), respectively. This yielded coefficients of variation of 5.0% for ⟨D⟩ (range 0.0 for CS to 8.51% for CGH) and 9.8% for FA (range 0.0 for CS to 12.3% for CGH), which compares well with values for other studies using ROI analysis (Shenkin *et al.*, 2005).

Initial comparisons between FA and ⟨D⟩ values from corresponding ROIs in left and right hemispheres revealed hemispheric differences in all regions either in FA, ⟨D⟩, or both. Therefore, all the reported analyses were conducted for hemispheres separately (Table 3). Group comparisons between asymptomatic carriers and controls revealed no significant differences in either FA or ⟨D⟩ values. However, group comparisons between familial Alzheimer's disease patients and controls showed that familial Alzheimer's disease patients had higher ⟨D⟩ in CGH and GCC bilaterally, left iFWM, and left sCC. Also, group comparisons between familial Alzheimer's disease patients and asymptomatic carriers showed that familial Alzheimer's disease patients had higher ⟨D⟩ in gCC bilaterally, left iFWM, right CGH, and left sCC.

Insert Table 3 about here

Relationship between DT-MRI metrics and behavioural tasks

To identify the ROIs which might be related to deficits in STM binding, the shape-colour binding condition was chosen for further analysis as this was the only condition of the STM binding task that differentiated between the three study groups. Performance on the PAL task was also included for comparison due to the reported sensitivity of this memory function to the early stages of Alzheimer's disease (Fowler *et al.*, 2002; Swainson *et al.*, 2001). Although in the current study asymptomatic carriers were not significantly impaired on the PAL, in previous studies this task accounted for a large proportion of variance between carriers and controls who were taken from the same population (Parra *et al.*, 2010). Our data show a significant group effect in the shape-colour binding task (model $P < 0.001$, adjusted $R^2 = 0.42$) and PAL task (model $P < 0.001$, adjusted $R^2 = 0.43$).

In the shape-colour binding task, better performance was significantly predicted by $\langle D \rangle$ values in bilateral gCC and, left iFWM, and left CGH (Table 4). FA values did not significantly predict task performance. When examining the groups separately, we found that task performance correlated significantly with $\langle D \rangle$ values in right mFWM ($r = -0.80$, $P = 0.036$) and left gCC ($r = -0.75$, $P = 0.04$) only in the familial Alzheimer's disease group (Figure 3). In the other groups the correlations were not significant (see Supplementary Table 3). The task ~ group*DT-MRI model with variables showing significant correlations revealed that the slope of the familial Alzheimer's disease group significantly differed from that of controls for both mFWM and bilateral gCC (all $P < 0.05$).

Insert Table 4 about here

Insert Figure 3 about here

In the PAL task, better performance was significantly predicted by FA values in left mFWM, right sCC, left CGH, and by ⟨D⟩ values in all ROI but right iFWM and right CS (see Table 4). When examining the groups separately, we found that task performance correlated significantly with FA values in left mFWM (r = 0.85, $P = 0.002$) and with ⟨D⟩ values in left mFWM (r = -0.69, $P = 0.036$), right mFWM (r = -0.66, $P = 0.048$), left iFWM (r = 0.70, $P = 0.036$), and left CGH (r = -0.72, $P = 0.036$) in the familial Alzheimer's disease group (Figure 3). Although the correlations in the AC group were all non-significant, the effect sizes were of middle or large magnitude as compared with small in the HC group (see supplementary table 3). The task ~ group*DT-MRI model with variables showing significant correlations revealed that the slope of the familial Alzheimer's disease group significantly differed from that of controls for FA values in left mFWM, ⟨D⟩ in left mFWM, left iFWM, and left CGH (all $P < 0.05$).

Discussion

The present study was designed to investigate whether white matter integrity detected with DT-MRI was associated with deficits in memory binding functions known to be sensitive to

the early stages of Alzheimer's disease. This hypothesis was assessed in a unique population of carriers of the mutation E280A- PSEN1 who were either in the asymptomatic stages or had recently met criteria for Alzheimer's disease. The main findings of this study were: (1) white matter integrity in frontal regions (mFWM) and in the anterior part of corpus callosum (gCC) accounted for a significant proportion of variance of STM binding performance. (2) White matter integrity in frontal regions (mFWM and iFWM) and in the hippocampal part of cingulum bundle (CGH) accounted for a significant proportion of variance in performance on the PAL task. (3) These associations proved significant in the clinical but not in the preclinical stages of familial Alzheimer's disease. Before we discuss the implications of these findings for our current understanding of memory decline in Alzheimer's disease, we briefly address the distinction between these two memory systems.

STM binding is an integrative memory function known to support the conjunction of features necessary to create objects' identity (Staresina and Davachi, 2010). Such a function relies on regions along the visual ventral stream but is independent of the hippocampus (Parra *et al.*, 2014). Associative memory is an integrative memory function responsible for linking aspects of complex experiences, each with own identity, into relational representations. Such a memory function cannot be carried out without an intact hippocampus (Mayes *et al.*, 2007; Moses and Ryan, 2006). Conjunctive (STM binding) and relational (associative memory) binding functions have been found to dissociate also in STM (Parra *et al.*, 2013). A recent hypothesis paper has suggested that context-free memory (e.g., STM binding) declines in the sub-hippocampal phase of Alzheimer's disease, which seems to occur very early in the disease process (Braak stages I-II). However, context-rich memory (e.g., associative memory) is impacted during the hippocampal phase of Alzheimer's disease which appears to correspond to more advanced diseases stages (Braak stages III-VI) (Didic *et al.*, 2011). This ongoing debate is relevant to our current study as our data revealed different patterns of

dissociation for behavioural and DT-MRI variables.

Unlike previous studies which have consistently reported differences in white matter integrity in the pre-symptomatic stages of familial Alzheimer's disease (Ringman *et al.*, 2007; Ryan *et al.*, 2013), in the present study we failed to find significant differences in DT-MRI metrics between asymptomatic carriers and controls. There are some key differences between the present study and those reported earlier which may explain this lack of replication. First, Ringman *et al.* (2007) investigated DT-MRI metrics in a heterogeneous group of carriers of different mutations either in the PSEN1 (A431E, n=11; L235V, n=7; G206A, n= 1) or APP gene (V717I, = 4). This raises the question of whether such diverse genotypes may yield phenotypic expressions which contributed differently to the reported outcomes. In our study we assessed a sample taken from a population which carries a single mutation of the PSEN1 (i.e., E280A). Second, in the study by Ryan *et al.* (2013), they investigated an even more genetically heterogeneous sample of carriers of PSEN1 mutation who were also older than the carriers investigated in the present study (M=37.8, SD=4.7). Age is an important factor in these dominantly inherited forms of Alzheimer's disease as it unequivocally indicates time to clinical expression. It has been recently observed that the PSEN1 mutation affecting the individuals from the Colombian kindred (i.e., E280A) leads to accumulation of amyloid deposits from 28 through 37 years of age (Fleisher *et al.*, 2012). The asymptomatic carriers investigated here had a mean age of 35. The contributions of the amyloid pathology to white matter disruptions in Alzheimer's disease are well known (Racine *et al.*, 2014). These earlier findings together with our current results suggest that our sample of E280A- PSEN1 mutation carriers was in a stage of preclinical familial Alzheimer's disease where structural damage to white matter tracts is not yet evident.

Consistent with previous studies (Parra *et al.*, 2010; 2011), mutation carriers who did and did not meet criteria for familial Alzheimer's disease presented with significant STM binding

impairments. However, we observed that lower white matter integrity values were associated with STM binding impairments only in symptomatic carriers of the E280A- PSEN1 mutation. These differences were driven by increased ⟨D⟩ in frontal white matter and gCC. One other study investigating white matter integrity in familial Alzheimer's disease of which we are aware (Ringman *et al.*, 2007), showed disruption in left frontal white matter (ROI specified as two voxels in inferior frontal white matter). Although Ringman *et al.* (2007) implemented a definition of frontal white matter different from our own, our results are complementary and suggest that frontal white matter disturbances is an early anatomical signature of Alzheimer's disease (see also Oishi *et al.*, 2011). Furthermore the present study indicates that these white matter differences are associated with a decline of memory functions known to be affected in the preclinical stages of the disease, namely STM binding.

The role of frontal lobes (and connecting structures such as gCC) in working memory (Owen, 2000) and in binding functions in particular (Prabhakaran *et al.*, 2000; Sala and Courtney, 2007) has been recognized. Neuroimaging studies have documented the involvement of frontal regions, e.g. BA10 and dorso-lateral prefrontal cortex, during feature binding in working memory (Mitchell *et al.*, 2006; Prabhakaran *et al.*, 2000) and have suggested that changes in the activity of these regions are related to reduced binding abilities in older adults (Mitchell *et al.*, 2006). Here this association is further strengthened with the finding of prefrontal tract abnormalities related to STM binding deficits in individuals who have recently met criteria for familial Alzheimer's disease. Neuronal degeneration in Alzheimer's disease seems to begin in the neuronal periphery rather than in the cell body (Pigino *et al.*, 2003; *Stokin et al.*, 2005), and these early abnormalities appear to be associated with amyloid pathology (Gunawardena and Goldstein, 2001; Racine *et al.*, 2014). Factors such as altered myelin and oligodendrocytes, axonal degeneration, and vascular pathologies, are some proposed mechanisms (Bartzokis I *et al.*, 2007; Englund and Brun, 1990; Sjobeck *et al.*,

2005).

Severity of frontal white matter damage in Alzheimer's disease is closely related to parenchymal Abeta load (Chalmers *et al.*, 2005). Recent studies in E280A- PSEN1 mutation carriers taken from the same population studied here show that Abeta deposits in frontal regions begin at the age of 27 (26.2–28.9) and reach a plateau at the age of 36.2 years (35.1–39.3) (Fleisher *et al.*, 2012). This is more than 10 years before the average age of onset of this form of familial Alzheimer's disease. Of note, this is precisely the age at which we first see STM binding deficits in asymptomatic carriers of this mutation (Parra *et al.*, 2010; 2011), supporting the notion that these events, i.e. Abeta load, white matter degeneration and STM binding deficits, may be associated. However, contrary to our predictions, white matter integrity in the investigated ROI did not correlate with STM binding performance in the preclinical stages of familial Alzheimer's disease. This raises the question of what disease mechanism could trigger such an early memory decline. A potential account could be offered by the Neuroplasticity Hypothesis of Alzheimer's disease (Teter and Ashford, 2002). Early amyloidosis in the course of Alzheimer's disease may disrupt synaptic transmission leading to neuronal connectivity impairments (Spires-Jones and Hyman, 2014). White matter synaptic disruption precedes both white matter tract anomalies and neurodegeneration (Alix and Domingues, 2011; Sheng *et al.*, 2012). Therefore, different memory binding functions may be affected by different white matter events which would range from early synaptic dysfunction (conjunctive binding functions) to large scale network disruptions (relational binding functions). Such a hypothesis will benefit from future animal and human research.

Previous studies have reported that reduced white matter integrity in Alzheimer's disease leads to a disruption of the topological organization of large-scale structural networks (Lo *et al.*, 2010). We found that damage in mFWM and gCC were both related to poor performance on the STM binding task. The gCC is a major white matter structure hosting tracts (e.g.,

forceps minor) which connect the dorso-lateral prefrontal cortex across hemispheres (Barbas and Pandya, 1984). The strength of such connectivity seems to reflect changes in response to task demands (Tang *et al.*, 2010) or training (Takeuchi *et al.*, 2010). In the context of the present study, the association between poor performance on the binding condition of the STM task and increased ⟨D⟩ both in regional and trans-hemispheric white matter tracks may well reflect the demands for top-down attentional control. A recent fMRI study which used the same STM binding task as the current investigation reported binding-specific activation in posterior parietal regions (Parra *et al.*, 2014) which are also known to be part of the network supporting top-down attentional control (Gazzaley and Nobre, 2012). Therefore, the hypothesis that STM binding deficits may be explained, at least in part, by impaired structural connectivity early in the course of familial Alzheimer's disease seems to be one supported by these data.

This study also sheds light on the neural substrate of PAL deficits in Alzheimer's disease and demonstrates that lower white matter integrity in frontal regions (mFWM) and in the hippocampal part of cingulum bundle (CGH) accounts for a significant proportion of variance of performance on the PAL task in symptomatic carriers of the mutation. In line with previous studies, the patients with familial Alzheimer's disease assessed in the present study presented with associative learning deficits (Didic *et al.*, 2011; Lowndes and Savage, 2007). Associative memory, also known as relational binding (Mayes *et al.*, 2007; Moses and Ryan, 2006), appears to rely on the integrity of grey matter located in frontal regions and the hippocampus (Cer and O'Reilly, 2006) as well as on the effective connectivity between these regions (Fellgiebel and Yakushev, 2011; Yassa, 2011). There is evidence that associative learning declines in the prodromal stages of late-onset sporadic Alzheimer's disease (Fowler *et al.*, 2002; Swainson *et al.*, 2001). Previous neuroimaging studies in this population have demonstrated functional reorganization of medial temporal lobe structures, including the

hippocampus, when asymptomatic carriers with an average age of 33.7 years completed a face-name association task (Quiroz *et al.*, 2010). The authors suggested that functional changes within the hippocampal memory system occur years before cognitive decline in familial Alzheimer's disease. In fact, Parra *et al.* (2010; 2011) showed that STM binding and PAL exhibit a gradual and continued decline in groups of carriers whose age approached the average age of onset of this familial Alzheimer's disease variant. This decline stood out from the neuropsychological background and was found to be earlier and much steeper in the former function. The results presented here suggest that these very early PAL impairments in the early stages of familial Alzheimer's disease are not solely due to the impact of neurodegeneration on grey matter structures (see Quiroz *et al.*, 2013), but also to lower white matter integrity of those tracts connecting them.

It is worth noting that the analysis of DT-MRI metrics during PAL task performance revealed that this function relies on a more extended network than VSTM binding (Table 4). In previous studies we have found that STM binding was specifically affected by Alzheimer's disease relative to other non-Alzheimer's disease dementias (Della Sala *et al.*, 2012). We have suggested that a potential cause for this high specificity may lie at a neuroanatomical level. We have recently demonstrated that normal performance on the STM binding task presented here does not require an intact hippocampus (Parra *et al.*, 2013; 2014). In fact, we previously showed that performance on the STM binding and PAL tasks did not correlate in carriers of the mutations E280A- PSEN1 (Parra *et al.*, 2011). However, associative learning does decline in other non-Alzheimer's disease dementias (Clague *et al.*, 2005; Dimitrov *et al.*, 1999; Taylor *et al.*, 1990) and also in healthy ageing (Naveh-Benjamin *et al.*, 2007; Old and Naveh-Benjamin, 2008) rendering this task less specific both for the early detection of Alzheimer's disease and its differential diagnosis. In the present study we found that these functions previously dissociated at behavioural and anatomical level, also dissociate when the

integrity of white matter structure is considered, reinforcing the notion that memory binding functions in STM and in LTM have different neural correlates. The fact that PAL relies on a widespread network whereas the STM binding relies on more restricted network may well explain the different pattern of sensitivity and specificity shown by these two memory binding functions.

A question which may arise from this study is whether the associations between lower white matter integrity and specific memory impairments reported here are typical of Alzheimer's disease or a phenotypic expression of this specific mutation (i.e., E280A- PSEN1). There is no straightforward answer to this question as the links between genotype and phenotype in Alzheimer's disease are poorly understood (Holmes, 2002). However, a recent study suggests that when it comes to STM binding, sporadic and familial variants of Alzheimer's disease share a common phenotype (Parra *et al.*, 2011). Moreover, the findings of DT-MRI studies of both sporadic and familial variants have been complementary suggesting that though triggered by different mechanisms, the clinical expression of white matter damage in these forms of Alzheimer's disease may also share phenotypic features (see Gold *et al.*, 2012).

We acknowledge some limitations of this study. First, we used ROI analyses which introduce some subjective components to the placement of ROI structures of interest. However, we took great care in both the selection of ROIs and their placement, while checks were performed to ensure ROIs were placed solely in white matter structures. Furthermore, we assessed the inter-rater reliability as reported in a previous study (Pettit *et al.*, 2013) and this analysis confirmed a high reliability of this methods. We therefore consider it unlikely that issues related to the placement of ROIs may have had an influence on the results reported here. Second, the lack of associations between memory binding performance and DT-MRI metrics in asymptomatic carriers may reflect limited power due to the relative small sample assessed in this study. This is supported by the finding of middle to large effect sizes for the

correlational analyses between PAL performance and DTI-metrics in this group. Finally, it is worth mentioning some technical difficulties we encountered in identifying ROI such as the fornix, which is proving relevant as a biomarker for Alzheimer's disease (Oishi and Lyketsos, 2014). Although we failed to find significant associations between white matter integrity in the selected theory-driven ROI and STM binding performance in the preclinical stages of familial Alzheimer's disease, there may still be white matter structures which are relevant to this cognitive function. Nevertheless, we have provided reliable evidence of dissociation between the integrity of white matter structures and the two memory functions investigated here, namely STM binding and associative learning.

In sum, the present study showed that reduced white matter integrity, in frontal lobes, corpus callosum and medial temporal lobes, can account for memory binding impairments in familial Alzheimer's disease. In the early stages of familial Alzheimer's disease, white matter integrity explained deficits in memory binding functions which rely on large scale networks such as PAL. However, deficits in memory binding functions which need more selective networks do not seem to be accounted for by white matter disruption in asymptomatic individuals who will unequivocally develop familial Alzheimer's disease. Future studies should investigate what particular disease mechanisms underpin such an early memory decline.

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Supplementary material

Supplementary material is available.

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Figure Captions

Figure 1 Shape-colour binding task **(A)** Shapes used as stimuli **(B)** The three conditions used in the task

Figure 2 (A) Procedures for obtaining FA and ⟨D⟩ values for each ROI **(B)** ROIs meeting the criteria set for our study: (a) genu corpus callosum- GCC, (b) splenium corpus callosum- SCC, (c) middle frontal white matter – mFWM, (d) inferior frontal white matter – iFWM, (e) hippocampal part of the cingulum bundle – CGH, and (f) centrum semiovale – CS See Methods for a detailed description

Figure 3 Fitted regression lines for the Shape-Colour Binding (upper panel) and the Paired Associates Learning task (middle and lower panel) and DT-MRI variables for each group separately (HC = healthy controls, AC = asymptomatic carriers, FAD = familial Alzheimer's disease) in the regions where significant correlations between DT-MRI metrics and memory performance were found Dots show the observed data in raw values and lines represent fitted regression lines.

Table 1 Demographic variables and cognitive screening.

	FAD (*n* = 19) M (SD), (Range)	**AC (*n* = 18)** M (SD), (Range)	**HC (*n* = 21)** M (SD), (Range)	**ANOVA** ***F*, *P*-value**	**F**
Age	47.5 (6.4), (38-66)	35.1 (5.5), (24-43)	39.3 (83), (25-54)	15.46 (< 0.001)	
Education	7.3 (3.7), (2-14)	10.2 (3.9), (2-16)	10.3 (27), (4-13)	4.50 (<0.005)	
MMSE	23.6 (4.3), (17-30)	29.8 (0.4), (29-30)	29.6 (07), (28-30)	39.41 (< 0.001)	

AC = asymptomatic carriers, FAD = Familial Alzheimer's disease, HC = healthy controls, MMSE – Mini Mental State Examination

Significant ($p < 0.05$) tests highlighted in grey

Table 2 Neuropsychological performance for the 3 groups Beta values shown are standardized *P*-values for R^2 are FDR-corrected

Model (task ~ age + education + group)		**Predictor (beta and *P* values)**			
Task	**R^2 (*P* value)**	**Age**	**Education**	**Group 2 (AC)**	**Group 3 (FAD)**
PAL	0.47 (< 0.001)	-0.2 (0.108)	0.2 (0.130)	-0.2 (0.438)	-9.6 (< 0.001)
Complex Rey Figure – copy	0.30 (< 0.001)	-0.2 (0.221)	0.2 (0.159)	-0.02 (0.939)	-7.0 (0.011)
Complex Rey Figure - recall	0.55 (< 0.001)	-0.01 (0.953)	0.2 (0.090)	0.07 (0.686)	-1.19 (< 0.001)
Letter fluency (FAS)	0.09 (0.068)	-	-	-	-
Animal fluency	0.32 (< 0.001)	0.3 (0.059)	0.3 (0.036)	0.3 (0.209)	-9.0 (0.001)
Boston naming test	0.35 (< 0.001)	0.2 (0.105)	0.3 (0.04)	0.2 (0.475)	-10.0 (< 0.001)
Word list - immediate recall	0.45 (< 0.001)	< 0.01 (1.000)	0.02 (0.847)	0.1 (0.493)	-12.1 (< 0.001)
Word list - delayed recall	0.63 (< 0.001)	0.1 (0.449)	-0.01 (0.913)	-0.04 (0.830)	-15.6 (< 0.001)
Word list recognition	0.54 (< 0.001)	-0.1 (0.593)	-0.1 (0.423)	-0.01 (0.960)	-13.5 (< 0.001)
Trail Making Test A	0.38 (< 0.001)	0.3 (0.059)	-0.2 (0.047)	0.1 (0.827)	6.39 (0.009)
WCST number of categories	0.24 (0.002)	0.1 (0.320)	0.2 (0.164)	0.5 (0.030)	-6.3 (0.035)
WCST attempt to category	-0.07 (0.967)	-	-	-	-
Conditions of the VSTM Binding Task					
Shape only	0.57 (< 0.001)	-0.2 (0.077)	0.04 (0.697)	-0.3 (0.062)	-13.7 (< 0.001)

Colour only	0.37 (< 0.001)	-0.1 (0.333)	0.07 (0.529)	-0.2 (0.281)	-11.0 (< 0.001)
Shape-colour binding	0.42 (< 0.001)	-0.1 (0.458)	0.1 (0.242)	-0.68 (0.001)	-12.6 (< 0.001)

AC = asymptomatic carriers, FAD = Familial Alzheimer's disease, HC = healthy controls, WCST = Wisconsin Card Sorting Test Significant (p<005) tests highlighted in grey

Table 3 Significant group differences in DT-MRI measures in regions of interests *P*-values for R^2 are FDR-corrected

Model (DT-MRI ~ group)		**Predictor (beta and *P* values)**			**Pos (t a**
DT-MRI	**R^2 (*P* value)**	**Group 2 (AC)**	**Group 3 (FAD)**	**HC vs AC**	
FA left mFWM	0.04 (0.224)	-	-	-	
FA right mFWM	0.007 (0.417)	-	-	-	
FA left iFWM	0.03 (0.224)	-	-	-	
FA right iFWM	-0.005 (0.495)	-	-	-	
FA left gCC	0.06 (0.133)	-	-	-	
FA right gCC	-0.01 (0.568)	-	-	-	
FA left sCC	-0.03 (0.850)	-	-	-	
FA right sCC	-0.01 (0.527)	-	-	-	
FA left CGH	0.10 (0.069)	-	-	-	
FA right CGH	0.03 (0.224)	-	-	-	
FA left CS	-0.003 (0.481)	-	-	-	
FA right CS	0.06 (0.146)	-	-	-	
⟨D⟩ **left mFWM**	0.07 (0.133)	-	-	-	
⟨D⟩ **right mFWM**	0.08 (0.096)	-	-	-	
⟨D⟩ **left** iFWM	0.15	0.04	0.76	-0.2	

	(0.024)	(0.861)	(0.003)	(0.983)	
⟨D⟩ **right** iFWM	0.03 (0.234)	-	-	-	
⟨D⟩ **left gCC**	0.14 (0.024)	0.07 (0.781)	0.8 (0.003)	-0.3 (0.958)	
⟨D⟩ **right gCC**	0.13 (0.036)	-0.01 (0.969)	0.70 (0.007)	0.04 (0.999)	
⟨D⟩ **left sCC**	0.15 (0.024)	-0.2 (0.409)	0.63 (0.012)	0.8 (0.685)	
⟨D⟩ **right sCC**	0.005 (0.417)	-	-	-	
⟨D⟩ **left CGH**	0.16 (0.024)	0.3 (0.287)	0.85 (0.001)	-1.1 (0.533)	
⟨D⟩ **right CGH**	0.24 (0.005)	-0.1 (0.693)	0.86 (< 0.001)	0.4 (0.917)	
⟨D⟩ **left CS**	0.11 (0.055)	-	-	-	
⟨D⟩ **right CS**	0.005 (0.417)	-	-	-	

⟨D⟩ = Mean Diffusivity, AC = asymptomatic carriers, CGH = hippocampal part of cingulum bundle, CS = centrum semiovale, FA = Fractional Anisotropy, FAD = Familial Alzheimer's disease, gCC = genu of corpus callosum, HC = healthy controls, iFWM = inferior frontal white matter, mFWM = middle frontal white matter, sCC = splenium of corpus callosum
Significant (p<005) tests highlighted in grey

Table 4 Variance explained by DT-MRI parameters in task performance in the short-term memory binding task and the PAL task *P*-values are FDR-corrected

Model (task ~ DT-MRI)	**VSTM Shape-Colour Binding**		
	FA	⟨D⟩	**FA**
	R^2 (*P* value), Beta	**R^2 (*P* value), Beta**	**R^2 (*P* value), Beta**
Left mFWM	0.04 (0.157), 0.23	0.01 (0.276), -0.18	0.18 (0.007), 0.44
Right mFWM	0.05 (0.102), 0.27	0.02 (0.257), 0.19	0.02 (0.243), 0.20
Left iFWM	-0.02 (0.951), 0.009	0.10 (0.040), -0.34	0.00 (0.371), 0.15
Right iFWM	-0.00 (0.437), -0.13	0.08 (0.064), -0.31	0.01 (0.325), 0.16
Left gCC	-0.00 (0.414), 0.14	0.15 (0.009), -0.41	0.05 (0.115), 0.25
Right gCC	-0.01 (0.501), 0.11	0.16 (0.009), -0.42	-0.01 (0.501), 0.11
Left sCC	-0.02 (0.728), 0.06	0.03 (0.182), -0.22	0.06 (0.094), 0.27
Right sCC	-0.01 (0.501), 0.07	-0.02 (0.734), -0.06	0.10 (0.032), 0.35
Left CGH	-0.00 (0.414), 0.14	0.15 (0.009), -0.41	0.13 (0.015), 0.39
Right CGH	0.05 (0.112), 0.26	0.08 (0.066), -0.31	0.05 (0.107), 0.26
Left CS	-0.02 (0.782), -0.05	0.06 (0.094), -0.28	-0.02 (0.857), 0.03
Right CS	0.01 (0.325), 0.17	0.01 (0.299), -0.18	0.07 (0.071), 0.29

⟨D⟩ = Mean Diffusivity, CGH = hippocampal part of cingulum bundle, CS = centrum semiovale, FA = Fractional Anisotropy, gCC = genu of corpus callosum, iFWM = inferior frontal white matter, mFWM = middle frontal white matter, sCC = splenium of corpus callosum Significant (p<005) tests highlighted in grey

Supplementary Material

Supplementary Table 1. All the MNI coordinates for each of the ROI used in the analysis

		MNI coordinates					
ROI	Side	x, y, z	x, y, z	x, y, z	x, y, z	x, y, z	x, y, z
mFWM	left	-19, 37, 1	-26, 37, 1	-23, 44, 1	-19, 35, 8	-26, 35, 8	-21, 42, 8
	right	20, 37, 1	27, 37, 1	24, 44, 1	20, 35, 8	27, 35, 8	24, 42, 8
gCC	left	-10, 29, 10	-8, 30, 3				
	right	10, 30, 10	9, 30, 3				
sCC	left	-12, -44, 12	-10, -41, 19				
	right	15, -44, 12	12, -41, 19				
iFWM	left	-37, 15, 20	-37, 20, 15	-43, 11, 10			
	right	37, 15, 20	37, 20, 15	45, 12, 10			
CGH	left	-21,-34, -12	-21,-28,-17	-24, -24, -22			
	right	24,-31, -12	23,-26,-17	24, -22, -22			
CS	left	-22, 10, 36	-24, 0, 36	-26, -10, 36	-28, -20, 36	-26, -30, 36	-24,-40, 36
	right	22, 10, 36	24, 0, 36	26, -10, 36	28, -20, 36	26, -30, 36	24, -40, 36

CGH = hippocampal part of the cingulum bundle, CS = centrum semiovale, gCC = genu of corpus callosum, iFWM = inferior frontal white matter, mFWM = middle frontal white matter, sCC = splenium of corpus callosum.

Supplementary Table 2. Procedures followed for placement of ROI.

ROI	**Box size (voxels)**	**No. of boxes**	**Total size (voxels)**	**Total size (mm^3)**
mFWM	3 x 3 x 1	6	108	957.13
gCC	3 x 3 x 1	3	54	478.56

sCC	3 x 3 x 1	3	54	478.56
iFWM	3 x 3 x 1	3	54	478.56
CGH	3 x 3 x 1	3	54	478.56
CS	3 x 3 x 1	6	108	957.13

CGH = hippocampal part of the cingulum bundle, CS = centrum semiovale, gCC = genu of corpus callosum, iFWM = inferior frontal white matter, mFWM = middle frontal white matter, sCC = splenium of corpus callosum.

Supplementary Table 3. Correlational analyses between behavioural variables and DT-MRI metrics for the three groups.

	Correlation between Shape-Colour Binding and DT-MRI					
	HC			AC		
ROI	**r**	***P* (FDR-corrected)**	**Cohen-*d***	**r**	***P* (FDR-corrected)**	**Cohen-*d***
MD right mFWM	**0.44**	0.9620	0.98	-0.19	0.6992	0.40
MD left gCC	0.23	0.9620	0.47	0.27	0.5126	0.55

	Correlation between PAL and DT-MRI					
	HC			AC		
ROI	**r**	***P* (FDR-corrected)**	**Cohen-*d***	**r**	***P* (FDR-corrected)**	**Cohen-*d***
FA left mFWM	-0.14	0.9620	0.29	0.41	0.3154	0.90
MD left mFWM	0.19	0.9620	0.39	-0.44	0.2622	0.97
MD right mFWM	-0.01	0.9620	0.02	-0.46	0.2622	1.02
MD left iFWM	0.07	0.9620	0.13	-0.35	0.3634	0.75
MD left CGH	-0.02	0.9620	0.03	-0.46	0.2622	1.05